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INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 7 : <b>H01B 1/12, H01L 51/20, C08G 61/10</b>		A1	(11) International Publication Number: <b>WO 00/60612</b> (43) International Publication Date: <b>12 October 2000 (12.10.00)</b>
(21) International Application Number: <b>PCT/GB00/01288</b> (22) International Filing Date: <b>5 April 2000 (05.04.00)</b>  (30) Priority Data: <b>9907802.4 6 April 1999 (06.04.99) GB</b>  (71) Applicant ( <i>for all designated States except US</i> ): CAMBRIDGE DISPLAY TECHNOLOGY LIMITED [GB/GB]; 181A Huntingdon Road, Cambridge CB3 0DJ (GB).		(81) Designated States: AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, CA, CH, CN, CR, CU, CZ, DE, DK, DM, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, TZ, UA, UG, US, UZ, VN, YU, ZA, ZW, ARIPO patent (GH, GM, KE, LS, MW, SD, SL, SZ, TZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GW, ML, MR, NE, SN, TD, TG).	
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(54) Title: METHOD FOR DOPING A POLYMER			
(57) Abstract			
<p>A method for forming a conjugated polymer which is doped by a dopant comprising the steps of: (a) adding a doping agent comprising a dopant moiety to a solution comprising the conjugated polymer or a precursor thereof and, optionally, a second polymer, the dopant moiety being capable of bonding to the conjugated polymer, precursor thereof or the second polymer; (b) allowing the dopant moiety to bond to the conjugated polymer, precursor thereof or the second polymer to perform doping of the conjugated polymer; characterised in that the amount of doping agent added in step (a) is less than the amount required to form a fully doped conjugated polymer.</p>			

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**D scription**

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## METHOD FOR DOPING A POLYMER

10 The present invention relates to a method for doping a conjugated polymer. Polymers preparable according to the method of the

15 Doping of conjugated polymers (polymers with pi-conjugated backbone structures and/or pi-conjugated pendant groups) with strong protonic acid (p-doping) or strong oxidising (p-doping) or reducing agents (n-doping) is well established in the literature. However, the doping proceeds readily to completion in the presence of a stoichiometric or excess amount of dopants. The chemical driving force for maximum doping is very high, so that it is difficult to arrest the doping level at an intermediate value. The system achieves the maximum doping with about 10-50% of the conjugated repeat units doped depending on the polymer system. For poly(p-phenylenevinylenes) and polyacetylenes, this is typically 10-20%; for polythiophenes, 20-30%; for polyanilines, 40-50%. This maximum level of doping imparts a high level of electrical conductivity of the order of 1-1000 S/cm to the polymers, depending on the nature and type of the polymers and dopants used, so that they become conducting polymers in the process. The bulk carrier concentration is then roughly of the order of  $10^{20} / \text{cm}^3$  to  $10^{21} / \text{cm}^3$ .

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However, this high level of doping is unnecessary or even undesirable for some applications. For example, for a 1- $\mu\text{m}$  thick film (which is typical of the vertical thickness of photonic structures) having a conductivity of  $10^{-6}$  S/cm, only a modest 1-V potential difference is required to drive a practical device current density of  $10 \text{ mA/cm}^2$  through the film thickness direction. Therefore, film conductivities of the order of  $10^{-6}$ - $10^{-7}$  S/cm (typical of the semiconducting range) are already sufficient for these films to be employed in semiconducting photonic structures such as distributed Bragg reflectors and waveguides.

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5 Furthermore, when the films are doped to the maximum, such as  
achieved by straightforward exposure to strong acids or oxidants,  
their optical properties change in drastic ways owing to the  
formation of new sub-gap transitions that change the refractive  
10 indices of the films and cause parasitic absorption of any  
emitted light. Both these factors are not desirable or  
acceptable for photonic applications. Therefore control of the  
bulk carrier concentration between  $10^{17} / \text{cm}^3$  to  $10^{20} / \text{cm}^3$ , at an  
15 intermediate doping-level at least about one order of magnitude  
less than the maximally-doped case, is crucial.

20 Applied Physics Letters, volume 73, Number 2, pages 253-255  
(1998) reports a study of the Hall mobility and the carrier  
concentration of a conjugated polymer, namely polythiophene, as a  
25 function of the electrochemical doping level. The doping level  
of the polymer is changed by varying the oxidation potential i.e.  
by potentiometric control.

30 Synthetic Metals, 68, pages 65-70 (1994) is concerned with field-  
effect mobility and conductivity data obtained from two different  
amorphous organic semiconductors which can be doped to a range of  
different conductivities.

35 Synthetic Metals, 89, page 11-15 (1997) investigates the doping  
and temperature dependence of the conductivity of poly(p)-  
phenylene vinylene) (PPV).

40 Synthetic Metals, 55-57, page 3597-3602 (1993) investigates  
electrical conductivity of  $\alpha,\alpha'$  - coupled dodecathiophene as a  
function of both dopant level and time.

45 Synthetic Metals, 30, page 123-131 (1989) discloses a  
relationship between acid strength and ionization potential of a  
50 conjugated polymer that will give a highly conductive doped  
complex.

5        Applied Physics Letters, volume 72, page 2147-2149 (1998)  
describes a doped hole transporting polymer. Differing levels of  
doping are realized by adjusting the co-evaporation rates of  
10      polymer and dopant material.

15      The methods used to achieve different levels of doping in the  
above systems are not satisfactory for controlling the doping  
level to such a degree so that a balance between optical and  
electrical property of the doped polymer can be struck.

20      In view of the above, there remains a need to develop a method  
for preparing polymers which are doped to a controlled, low or  
intermediate level which is both simple and cost effective. It  
is envisaged that polymers doped to such a level will be  
25      particularly useful in devices such as those referred to below in  
order to avoid the disadvantages associated with polymers that  
are doped to a high level. These disadvantages include intense  
sub-group absorptions, changes in the optical properties of the  
polymer and degradation of the photonic structure of the polymer.  
30      Using polymers that are doped to a controlled, low level or  
intermediate it will be possible to strike a balance between  
optical and electrical properties of an organic semiconductor  
when used in an optoelectronic device.  
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40      The present invention aims to provide a method for forming a  
conjugated polymer that is partially doped. The present  
invention further aims to provide a polymer preparable according  
to the method of the present invention and uses of such polymers.

45      Accordingly, the present invention provides a method for forming  
a conjugated polymer which is doped by a dopant comprising the  
steps of:

50      (a) adding a doping agent comprising a dopant moiety to a  
solution comprising the conjugated polymer or a precursor thereof  
and, optionally, a second polymer, the dopant moiety being

5 capable of bonding to the conjugated polymer, precursor thereof or the second polymer;

10 (b) allowing the dopant moiety to bond to the conjugated polymer, precursor thereof or the second polymer to perform doping of the conjugated polymer, characterised in that the amount of doping agent added in step (a) is less than the amount required to form a fully doped conjugated polymer.

15 The present invention further provides a conjugated polymer that is doped to a controlled, low or intermediate level which is preparable according to the method of the present invention.

20 The present invention still further provides a photonic device including a polymer according to the present invention.

25 One embodiment of the present invention provides a method for forming a partially doped polymer material, comprising: adding a doping agent to the polymer or a precursor thereof, the doping agent being capable of bonding to the precursor or the polymer chain; and causing the doping agent to leave the precursor or the polymer chain to form a dopant capable of doping the polymer chain; wherein fewer moles of the doping agent are added than would be numerically sufficient to fully dope the polymer chain. Also, the present invention provides a partially doped polymer material formed by that method. Further, the present invention provides a device/structure (such as a photonic device) that includes such a material.

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55 The conjugated polymer or its precursor is:

(i) derivatised with a controlled concentration (typically at the level less than 10-20% of the amount required for full doping) of a dopant moiety(ies) or its(their) precursor form(s); or

(ii) blended together with a polymer partner (the second polymer), which may or may not be a conjugated polymer itself,

5 which is derivatised with such moieties to give the equivalent dopant concentration.

10 Photonic structures are then fabricated from the partially doped polymer materials, including higher-order blends and composites, containing these modified conjugated polymers by film-forming techniques. A subsequent thermal, irradiation or chemical activation step may be required to generate the active dopant to 15 dope the conjugated polymer.

20 In a first aspect of the invention, a method is provided to manipulate a precursor polyelectrolyte to give a controllable partially-doped conjugated polymer after elimination. The method involves replacement of a fraction of the counter-anions of the 25 precursor polyelectrolyte by acid anions, such as sulfonates, phosphonates, phosphates, etc, of benzene, naphthalene and other organic derivatives while the precursor polyelectrolyte is in solution. These anions are converted during thermal elimination 30 to the corresponding strong organic acids which are less volatile and more compatible with the conjugated polymer than the conventional anions, such as chloride, bromide and acetate. This leads to a higher retention of a strong acid that could 35 favourably dope the polymer.

40 In a second aspect of the present invention, a method is provided for control over partial doping of a host conjugated polymer by blending with measured amounts of another substantially-miscible 45 polymer (the "second polymer") which is derivatised with a small fraction of dopant groups such as sulfonic acid, phosphonic acid or their precursors. The second polymer provides a means to distribute substantially homogeneously a controlled amount of dopant groups into the host conjugated polymer matrix. For this 50 to occur, the second polymer must be co-soluble in the same solvent used to deposit the desired conjugated polymer film, and preferably not undergo phase segregation in the matrix. This can

5       be achieved by derivatising to form a doped second polymer with a  
small fraction (usually less than 50mol%) of the dopant groups.  
10      If the derivatisation reaction is carried too far, the material  
produced tends to be no longer soluble in the common hydrocarbon  
solvents used to solubilise the conjugated polymers because of  
strong interaction of the polar dopant groups.

15      In a third aspect of the present invention, a method is provided  
for control over partial doping of a host conjugated polymer in  
solution by derivatisation with measured amounts of the dopant  
20      moieties, such as sulfonic acid, phosphonic acid or their  
precursors thereby, in effect, creating a copolymer. The order  
of the reaction may be inverted. Either the polymer can be  
formed first and then derivatised with a small mole fraction of  
25      the dopant; or the monomer could be derivatised first with the  
dopant group or its precursor and then incorporated at a small  
mole fraction into the primary conjugated polymer. The aim is to  
distribute substantially homogenously a controlled amount of  
30      dopant groups into the conjugated polymer matrix.

35      The present invention will now be described in more detail with  
reference to the attached drawings in which:

40      Figure 1 shows the reaction scheme according to Example 1. The  
scheme is applicable to conjugated polymers that are fabricated  
by thermal elimination of a cationic precursor polyelectrolyte.  
An example of such a polymer is PPV. In Figure 1, X is an  
optional alkyl or aryl spacer group, OR<sup>-</sup> and OR'<sup>-</sup> are optional  
alkoxy groups, D<sup>-</sup> is a precursor dopant moiety, for example,  
PO<sub>3</sub>H<sup>-</sup>, SO<sub>3</sub><sup>-</sup> or OPO<sub>3</sub>H<sup>-</sup>, y ≤ 0.05 and n ≥ 10.

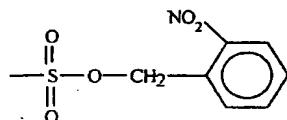
45      Figure 2a shows a polymer blend preparable according to the  
reaction scheme of Example 2. Example 2 is generally applicable  
to soluble conjugated polymers. Examples of such polymers  
50      include alkyl- and alkoxy- derivatives of PPV, poly(fluorenes)

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5 and their copolymers. "A" is a conjugated polymer host that is  
 blended with "B", the second polymer, that is conjugated or non-  
 conjugated. D is a non-precursor dopant moiety such as PO<sub>3</sub>H<sub>2</sub>,  
 10 SO<sub>3</sub>H or CF<sub>2</sub>COOH and n is as defined for figure 1.

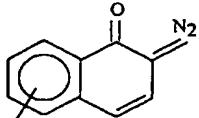
15 Figure 2b shows two copolymers preparable according to the  
 reaction scheme in Example 3. Example 3 is generally applicable  
 to soluble conjugated polymers. Examples of such polymers  
 include alkyl- and alkoxy- derivatives of PPV, poly(fluorenes)  
 and their copolymers. OR', OR'', X, D, n and y are as defined  
 20 for Figures 1 and 2a.

25 Figure 3 shows two reaction schemes for activating a precursor  
 dopant moiety, D, that is (a) bonded to a second polymer in a  
 blend or (b) part of a co-polymer system. D suitably may be SO<sub>3</sub>H  
 and D' suitably may be

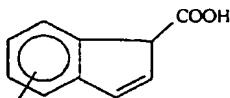


OR', OR'', y, n and X are as defined for Figure 1.

35 Figure 4 shows a reaction scheme for activating a precursor  
 dopant moiety D' that is part of a co-polymer system. Suitably  
 D' may be



45 and D may be



OR', OR'', y, n and X are as defined for Figure 1.

5       Figure 5 shows a reaction scheme for activating a precursor  
dopant moiety D' that is part of a co-polymer system. Suitably  
D' may be  $\text{SO}_3\text{R}$  or  $\text{PO}_3\text{R}_2$  and D may be  $\text{SO}_3\text{H}$  or  $\text{PO}_3\text{H}_2$ . R is a leaving  
10 group. OR', OR'', y, n and X are as defined for Figure 1. PAG,  
a photoacid generator, suitably is a diaryliodonium salt,  
triarylsulfonium salt or other onium salt.

15       Figure 6 shows an example of a polymer according to the present  
invention including a dopant moiety that is a redox group.  
Suitably D' may be ferrocenium or viologen. OR', OR'', X, n and  
y are as defined in Figure 1.

20       Figure 7 shows schematically the energy level structure of a DBR  
formed by means of partially doped conjugated polymer materials.  
la and lb are electrodes. 2 is an emissive layer. 3a-3f are  
25       polymer layers which form a "mirror structure". The HOMO and LUMO  
levels of the polymer layers 3a-3f are shown.

30       The conjugated polymer according to the present invention may be  
a homopolymer, copolymer, blend or composite material of  
conjugated polymers. For the purposes of the present invention,  
a conjugated polymer is defined as a polymer with a partially or  
fully  $\pi$ -conjugated backbone and/or  $\pi$ -conjugated pendent groups.  
35       The conjugated polymer after doping is preferably partially  
conducting. The conjugated polymer after doping is preferably  
partially semi-conducting.

40       The present invention realizes the incorporation of an amount of  
dopant, or its precursor, into a polymer film, via chemical  
derivatisation on the conjugated polymer chain itself or chemical  
45       derivatisation on another polymer partner (the second polymer)  
with which the first polymer is to be blended or copolymerised. The  
second polymer may or may not be conjugated.

50       The dopant level of a polymer produced according to the present

5 method is stable and readily controllable.

10 Preferably, the amount of doping agent added in step (a) is in  
the range of less than 10-20%, preferably 1 to 10%, of the amount  
required to form a fully doped conjugated polymer. Accordingly,  
15 the polymer produced in accordance with the present method,  
preferably, is doped to a level of less than 10-20% compared to  
full or maximum doping. More preferably, the amount of doping  
agent added in step (a) is sufficient to form a 0.001% to 5%  
20 doped conjugated polymer. Even more preferably, the amount of  
doping agent added in step (a) is sufficient to form a 0.1 to 1%  
doped conjugated polymer. The polymer produced in accordance  
with the present method, preferably, will have one doped site per  
10<sup>2</sup>-10<sup>4</sup> repeat units.

25 The conductivity of the polymer after doping is suitably more  
than 10<sup>-9</sup>S/cm and less than 1S/cm, preferably 10<sup>-8</sup>S/cm to 10<sup>-3</sup>S/cm,  
or preferably 10<sup>-6</sup> to 10<sup>-2</sup>S/cm. The conductivity of the polymer  
after doping is suitably less than 1S/cm. Preferably, the  
30 conductivity of the polymer after doping is less than 10<sup>-2</sup>S/cm or  
10<sup>-3</sup>S/cm. It is envisaged that the conductivity of the polymer  
after doping also may be less than 10<sup>-4</sup>S/cm or 10<sup>-5</sup>S/cm. It is  
35 envisaged that the conductivity may be in the range from 10<sup>-9</sup>S/cm  
to 10<sup>-13</sup>S/cm, and preferably, in the range from 10<sup>-9</sup>S/cm to  
10<sup>-3</sup>S/cm or 10<sup>-6</sup>S/cm to 10<sup>-2</sup>S/cm. The amount of dopant that is  
added is preferably an effective amount to achieve a conductivity  
40 in such a range.

45 In an alternative definition of a polymer preparable in  
accordance with the present method, the polymer is doped to a  
level of 10<sup>17</sup>-10<sup>19</sup> cm<sup>-3</sup>.

The doping agent may bond to the precursor or polymer chain by  
replacing a leaving group on the chain.

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5 In one embodiment of the present invention, the doping agent is a protonic acid doping agent. Suitable dopant moieties include a phosphonic acid group, a sulphonic acid group, a fluoroalkyl carboxylic acid group or an indene carboxylic acid group.

10 Where the dopant moiety comprises a precursor to the dopant, the precursor preferably comprises phosphonate or sulfonate.

15 If the dopant is incorporated in the precursor form, subsequent activation to generate the active dopant to dope the polymer may be necessary. This activation could be by thermal, irradiation, chemical or other means. Obviously, this would be unnecessary if the dopant is already incorporated in the active form.

20 In a further aspect of the present invention, the method also includes a step of causing the dopant to dissociate, for example by the application of light and/or heat. This involves cleaving the dopant moiety from the conjugated polymer, precursor thereof or the second polymer after the dopant moiety has been allowed to bond to it in step (b). This additional step enables the dopant to be dispersed uniformly or substantially uniformly into the polymer matrix comprising the conjugated polymer or precursor thereof and, optionally, the second polymer. This renders the dopant substantially non-diffusing and non-volatile.

25 30 35 Where the dopant moiety bonds to a precursor of the conjugated polymer, the method further comprises a step of forming a conjugated polymer from the precursor thereof.

40 45 The step of causing the doping agent to leave the polymer chain may be effected by heating. The step of causing the doping agent to leave the polymer chain may result also in conjugation of the polymer and/or formation of the polymer from the precursor.

50 Optionally, the dopant moiety may bond to the conjugated polymer,

5 precursor thereof or the second polymer in step (b) via spacer group X. Suitable spacer groups include, but are not limited to, alkyl and aryl groups.

10 The conjugated polymer according to the present invention may be any conjugated polymer and, suitably, may comprise precursor polyelectrolyte PPV or substituted PPVs. The dopant moiety counterion Y may comprise a phosphonate, sulfonate, phosphate, antimionate, borate, molybdate. These counterions may form a side-chain attached to the polymer backbone when they bond to the precursor conjugated polymer.

15 20 Non-precursor acid dopants include (a) phosphonic acid, (b) sulfonic acid, (c) fluorocarboxyl acid groups.

25 30 Precursor acid dopants include (a) o-nitrobenzyl sulfonate side-chains (converting to sulfonic acid group upon irradiation), see figure 3; (b) diazonaphthaquinone sulfonate side-chains (converting to indene carboxylic acid upon irradiation), see figure 4; (c) phosphonate or sulfonate ester side-chains, together with an incorporated photoacid generator (PAG) such as one of the onium salts (the onium salts generating a strong protonic acid upon irradiation which cleaves the sulfonate or phosphonate ester leaving group to the corresponding acid), see figure 5. See for example, A. Reiser "Photoreactive polymers: the science and technology of resists," John Wiley & Sons, New York, 1989.

35 40 45 50 The conjugated polymer according to the present invention may comprise poly(alkylthiophenes) and poly(alkylfluorenes) or their partners. They should be derivatised with a dopant moiety Y comprising a protonic acid group. Suitable photonic acid groups include phosphonic acid, sulfonic acid, carboxylic acid or their precursor in the form of esters, anhydrides, azides, hydrazides, amides, acid chlorides. The precursor form is capable of

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5                   converting to the active protonic acid form under irradiation,  
10                  thermal exposure, or by reaction with another chemical agent that  
                      may be originally deposited with the film or subsequently  
                      introduced to the film. In addition, the acid group or its  
                      precursor form could be spaced from the polymer main-chain by an  
                      alkyl or aryl spacer and could also be attached as a separate  
                      functional unit on the polymer chain.

15                  A further class of suitable dopant moieties for use in the  
                      present method include redox groups based on TCNQ, DDQ, TTF,  
                      ferrocene, viologen, iron(III) chelates, or their precursors.  
20                  The precursor form is capable of converting to the active form  
                      under irradiation, thermal exposure, or by reaction with another  
                      chemical agent. These groups could also be spaced from the  
                      polymer main chain by an alkyl or aryl spacer or attached to  
                      separate functional units on the chain. The redox group could  
                      accept electrons or donate electrons to the conjugated units,  
                      thereby p-doping and n-doping the conjugated units, respectively.

30                  Partially doped materials formed, for example, as described above  
                      could be used to form photonic structures such as distributed  
                      Bragg reflectors (potentially pumped reflectors), confinement  
                      heterostructures etc. Some examples of device structures which  
                      particularly advantageously may include a partially doped  
                      conjugated polymer preparable according to the present method are  
                      described in our co-pending UK patent application number  
                      9815271.3, the contents of which are incorporated herein by  
                      reference.

45                  The photonic device may include a plurality of layers of such  
                      doped materials, the layers alternative in their levels of  
                      doping. The device could be a mirror, for instance a distributed  
                      Bragg reflector.

50                  A distributed Bragg reflector (DBR) consists of a stack of

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5 regularly alternating higher- and lower-refractive index dielectrics (light transmissive materials) fabricated to fulfil  
the Bragg condition for reflection at particular wavelengths.  
10 This occurs when the optical path of the periodicity in the dielectric stack corresponds to half a wavelength, and the reflectivity is further optimised when the DBR stack obeys the equation:  $\frac{4}{\lambda} \lambda = n_1 d_1 + n_2 d_2$  and for the best performance, the DBR  
15 stack obeys the equation:  $\frac{4}{\lambda} \lambda = n_1 d_1 = n_2 d_2$ ,  
where  $n_1$ ,  $n_2$  are the respective refractive indices;  $d_1$ ,  $d_2$  are the corresponding component film thicknesses in the DBR; and  $\lambda$  is the desired reflection wavelength.

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Figure 7 shows schematically the energy level structure of a DBR formed by means of partially doped conjugated polymer materials. The doping of the materials is controlled so that the HOMO or LUMO levels (depending on whether the mirror is between the anode or the cathode and the emissive layer) of alternate layers of the mirror are at least approximately aligned so that the passage of holes/electrons through the mirror is not significantly impeded at the boundaries between layers of the mirror. The thicknesses of the layers of the mirror are chosen to satisfy the conditions for reflection. The refractive index of the layers is related to their band gaps, but by means of partial doping the HOMO/LUMO levels can be aligned independently of the band gaps.

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40 Since the DBR is formed of conjugated material it could be electrically-pumped to generate photons in addition to reflecting.

45 The present invention will now be described by way of non-limiting illustrative examples.

50 Examples

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Example 1Partial doping of poly(p-phenylenevinylene) by anion exchange of  
the precursor poly(p-xylylene-alpha-tetrahydrothiophene) route

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This is an exemplification of the scheme outlined in Figure 1.  
This Example illustrates the first aspect of the present invention.

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Example 1A:Preparation of partially doped PPV

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To effect replacement of chloride by phenylphosphonate: 10 mL of 3 w/v% poly(p-xylylene-alpha-tetrahydrothiophenium chloride) (pre-PPV-C1) (1.3 mmol repeat unit) dissolved in methanol is mixed with 10 mL of 20 w/v% phenylphosphonic acid (13 mmol) dissolved also in methanol. The mixture is then dialysed against pure methanol through a dialysis membrane having molecular weight cut-off of 12,000. This gives a poly(p-xylylene-alpha-tetrahydrothiophenium phenylphosphonate) precursor (pre-PPV-PA) polymer which is retained by the dialysis membrane. The retentate can then be concentrated to the desired concentration and blended with the parent poly(p-xylylene-alpha-tetrahydrothiophenium chloride), in the desired ratio for solution casting. This allows control over the level of doping in the final product.

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To analyse the material:

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(1) A small volume of the methanol solution pre-PPV-PA was evaporated to give a white solid. Thermogravimetry experiments under nitrogen show this material exhibits a weight loss step extending from 150°C to about 300°C. This occurs over a wider range than for the parent poly(p-xylylene-alpha-tetrahydrothiophenium chloride) material which exhibits a weight loss step ending at about 200°C. This is despite the fact that phenylphosphonate, being a better leaving group than chloride, undergoes slow elimination from the PPV backbone event at room

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5 temperature. The greater thermal stability in thermogravimetry experiments is therefore due to the considerably lower vapour pressure (and hence smaller evaporation loss) of phenylphosphonic

10 acid. This confirms that greater retention of the phenylphosphonic acid occurs for the same temperature.

15 2) The pre-PPV-PA material in methanol is spin-cast onto glass substrates and then baked at 180°C under vacuum for 2 hours to effect conversion to the conjugated PPV. X-ray photoelectron spectroscopy confirms a significant retention of the PA: 7 mol% (relative to PPV repeat unit) retention of the PA compared to less than 0.5 mol% retention of Cl in the parent material.

20 25 (3) Photothermal deflection spectroscopy of a film of a precursor PPV counterbalanced by 10 mol% PA + 90 mol% Cl (made by blending) shows sub-gap absorption strength of 60 cm<sup>-1</sup> at 750-nm wavelength. This corresponds to a doping level (that is, the ratio of ionized dopant-to-PPV repeat unit) of 0.1 mol% - 0.01 mol%.

30 Example 1 B:  
Diode structure including partially doped PPV

35 To demonstrate the improvement in electrical conductivity associated with partial doping according to the present invention diode structures with indium-tin oxide/poly(3,4-dioxy-thiophene):poly(4-styrenesulfonate) composite anodes and calcium cathodes were fabricated for active layers (i) and (ii) defined 40 in Table 1.

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Table 1

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Device structure	Drive voltage required to achieve current density of $1\mu\text{A}/\text{cm}^2$	Drive voltage required to achieve current density of $10\mu\text{A}/\text{cm}^2$
(i) Undoped 69-nm-thick PPV film with 50 vol% silica	5.0 V	7 V
(ii) Partially-doped PPV stack having a combined thickness of 207 nm for the films with 50 vol% silica and 171 nm for the neat films, and with an addition 105-nm-thick emitter polymer film	5.0 V	10 V

For the structure(i) with the undoped PPV polymer (dispersed with silica particles to change its refractive index), a large voltage is required to drive currents through a thin film of the material owing to the additional resistance offered by the silica particles. For the structure (ii) with the partially-doped PPV however, the resistance is clearly reduced by a considerable amount. Similar drive voltages can deliver comparable current densities through much thicker combined polymer film thickness. In the absence of doping, the required voltage is expected to increase as the square of the film thickness so that more than 50 V will be needed for  $1\mu\text{A}/\text{cm}^2$  in structure (ii).

At the same time, no deleterious absorptions in the sub-gap spectral region of the PPV occurs. This allows the material to be used in transmissive photonic structures.

Example 2:

Partial doping of organic-soluble poly(p-phenylenevinylene) and poly(fluorene) derivatives by blending with a second polymer bearing a small fraction of dopant acid groups

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This is an exemplification of the scheme in Figure 2a.

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Example 2A:Preparation of partially doped PPV and polyfluorene

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Poly(styrenesulfonic acid-co-styrene) copolymer (PSSH-co-PS) as the "second polymer" is blended in [alkoxylphenyl-PPV]-co-[dialkoxy-PPV] (P1) or poly(dialkylfluorene-co-triarylamine) (P2) as host.

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This illustrates the generality of the second aspect of the present invention.

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To prepare the PSSH-co-PS: 0.5 g of polystyrene (4.8 mmol repeat unit) is dissolved with heating into 5 mL anhydrous chloroform in a borosilicate glass reaction flask sealed with teflon-faced silicone rubber septa, and the mixture cooled to -8°C in a bath of calcium chloride and ice-water. 0.01 mL of chlorosulfonic acid (0.15 mmol) is dissolved into 2 mL of chloroform and then syringed into the PS polymer solution. A white cloudy mixture develops almost immediately. The mixture is warmed to room temperature after 30 minutes and 3 mL of water is added, and the mixture optionally refluxed. To work up, 40 mL of toluene is added and the white precipitate is washed and isolated twice by centrifuge. The precipitate is then purified by dissolving in tetrahydrofuran and re-precipitation from toluene. This material is insoluble in chloroform, methanol or toluene, but soluble in tetrahydrofuran from which good quality films can be cast.

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The difference Fourier-transform infrared spectrum of a thin film of the PSSH-co-PS cast on silicon substrates shows the asymmetric and symmetric S-O sulfonate bands at 1000-1200 cm<sup>-1</sup> and the appearance of the 2-adjacent hydrogen wagging vibration at 840-860 cm<sup>-1</sup>. This confirms successful sulfonation of PSSH-co-PS with an expected 1-2 mol% of PSSH. Increasing the PSSH content to 50 mol% leads to an intractable material that is insoluble in common solvents. Increasing the PSSH content further to near 100 mol% gives a material that is soluble in water and methanol. The

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5 PSSH-co-PS with a low PSSH content less than 10 mol% is therefore compatible with a range of conjugated polymers, and so can be used to regulate the level of doping in these materials.

10 Example 2B:  
A diode structure including a partially doped PPV or polyfluorene

15 To demonstrate that the PSSH-co-PS material with 2 mol% PSSH can be used to improve the electrical conductivity of the conjugated polymer host, we fabricated diode structures with indium-tin oxide anodes and aluminium cathodes for the following active 20 layers. The drive voltages for the selected diode current densities are show in Table 2.

25 Table 2

Device structure	Drive voltage required to achieve current density of 1 $\mu$ A/cm <sup>2</sup>	Drive voltage required to achieve current density of 100 $\mu$ A/cm <sup>2</sup>
(i) Undoped 1.05- $\mu$ m-thick P1 film	5.5 V	47 V
(ii) Partially-doped 1.05- $\mu$ m-thick P1 film with 1 w/w% of PSSH-co-PS	2.0 V	33 V
(iii) Partially-doped 1.05- $\mu$ m-thick P1 film with 10 w/w% of PSSH-co-PS	1.1 V	9 V
(iv) Undoped 1.65- $\mu$ m-thick P2 film	9.5 V	40 V
(v) Partially-doped 1.65- $\mu$ m-thick P2 film with 1 w/w% of PSSH-co-PS	5.5 V	25 V

45 For devices with the 1.05- $\mu$ m-thick P1 polymer film (that is, structures (i)-(iii)), a substantial reduction in drive voltage, for example from 47 V to 9 V at 100  $\mu$ A/cm<sup>2</sup>, is achieved upon doping with 10 w/w% of the PSSH-co-PS. At the same time, there 50 is no significant loss of transmission (less than 1% transmission loss) in the sub-gap spectral region of the host polymer. This is because the ratio of PSSH dopant-to-polymer repeat unit is

5 about 0.5 mol%, and the actual doping level (that is, the ratio of ionized PSSH-to-repeat unit) could be even lower depending on the ionization potential of the polymer.

10 For devices with the 1.65- $\mu\text{m}$ -thick P2 polymer (that is, structures (iv) and (v)), a similar reduction is observed, from 40 V to 25 V at  $100 \mu\text{A}/\text{cm}^2$ , upon doping with 1 w/w% of the PSSH-co-PS. In this case, doping with 10 w/w% of the PSSH-co-PS gives phase separation as evident by cloudy nature of the deposited films.

15 20 These examples demonstrate the use of partially-derivatised polymeric dopants in a blend to regulate the doping-level and hence improve the electrical conductivity of conjugated polymer films for photonic structures.

25 Example 3:  
30 Partial doping of an organic-soluble poly(fluorene) derivative by partial derivatisation with a small fraction of acid groups

35 40 This is an exemplification of the scheme outlined in Figure 2b.

45 Example 3A:  
50 Preparation of a partially doped poly(fluorene)

In this example, the synthesis and use of a partially sulfonated poly(fluorene-co-triphenylamine) (SP2: S denotes sulfonation) is used to illustrate the generality of the third aspect of the present invention.

55 To prepare the SP2-co-P2: 0.1 g of P2 (0.25 mmol fluorene repeat unit) is dissolved into 5 ml of anhydrous chloroform in a borosilicate glass reaction flask sealed with teflon-faced silicone rubber septa, and the mixture cooled to  $-8^\circ\text{C}$  in a bath of calcium chloride and ice-water. Chlorosulfonic acid is

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5 dissolved into chloroform to give an equivalent of 0.0025 ml of  
chlorosulfonic acid (0.037 mmol) per ml of chloroform. 1 mL of  
10 this solution is then syringed into the P2 polymer solution. An  
orange solution is obtained almost immediately. The mixture is  
warmed to room temperature after 30 minutes, and 40 mL of acetone  
15 is then added to produce a white precipitate. The precipitate is  
recovered by centrifugation and then purified by dissolving in  
chloroform and re-precipitating from methanol. This SP2-co-P2  
material is soluble in chloroform, toluene and tetrahydrofuran  
but insoluble in methanol and acetone.

20 The difference Fourier-transform infrared spectrum of a thin film  
of the SP2-co-P2 material cast on silicon substrates shows (i)  
the asymmetric and symmetric S-O sulfonic bands at  $1355\text{ cm}^{-1}$  and  
25  $1175\text{ cm}^{-1}$  respectively, (ii) the S-O band at  $905\text{ cm}^{-1}$ , (iii) the  
appearance of the one-hydrogen wagging vibration at  $860-880\text{ cm}^{-1}$ .  
This confirms sulfonation of SP2-co-P2 with an expected 5-10 mol%  
of sulfonic acid groups.

30 To demonstrate that this derivatised material has a better  
electrical conductivity than its parent, we fabricated diode  
structures with indium-tin oxide anodes and aluminium cathodes  
35 for the following active layers. The drive voltages for selected  
diode current densities are shown in Table 3.

Table 3

Device structure	Drive voltage for current density of $1\mu\text{A}/\text{cm}^2$	Drive voltage for current density of $100\mu\text{A}/\text{cm}^2$
(i) Undoped 1.1- $\mu\text{m}$ -thick P2 film	10.5 V	31 V
(ii) Partially-doped 1.1- $\mu\text{m}$ -thick P2 film with 1 w/w% of SP2-co-P2	4.5 V	21 V

50 A significant reduction in drive voltage, for example from 31 V  
to 21 V at  $100\mu\text{A}/\text{cm}^2$  in 1.1- $\mu\text{m}$ -thick films, is obtained in the

-21-

5 presence of partial doping by an equivalent of 0.05 mol% - 0.1  
mol% of sulfonic acid groups. At the same time, there is no  
10 significant loss of transmission in the sub-gap spectral region  
of this P2 polymer.

15 This example therefore demonstrates the use of a controlled level  
of dopant derivatisation of the conjugated polymer to improve the  
electrical conductivity of conjugated polymer films for use in  
photonic structures.

20 Example 4:

25 Examples 2 and 3 were repeated but with the sulfonic acid polymer  
subsequently reacted with quantitative amounts of o-  
nitrobenzylbromide in chloroform or tetrahydrofuran before film  
formation to give the o-nitrobenzylsulfonate ester as the  
precursor dopant. The polymer was then blended with the host  
polymer as in Example 2 or used neat (similar to Example 3) in a  
30 suitable solvent and formed into a film. The precursor sulfonate  
ester group was then cleaved by UV exposure to generate the  
active sulfonic acid group in the film.

35 Example 5:

40 Examples 2 and 3 were repeated but with the sulfonic acid polymer  
subsequently reacted with excess of methylating agent such as  
diethylmethylsulfate before film formation to give the methylsulfonate  
ester as the precursor dopant. The polymer was then blended with  
45 small quantities of a photoacid generator such as  
diphenyliodonium chloride or other diaryliodonium,  
triarylsulfonium or other onium salts, and further optionally  
blended with the host polymer (such as in Example 2) or used  
substantially neat (similar to Example 3) in a suitable solvent  
50 and formed into a film. The polymer film was then exposed to  
light or heat to cleave the photoacid generator to produce a

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5 strong acid with then cleaves the sulfonate ester to the active  
10 sulfonic acid.

10 The present invention is not limited to the examples described  
above.

15 The applicant draws attention to the fact that the present  
invention may include any feature or combination of features  
disclosed herein either implicitly or explicitly or any  
generalisation thereof, without limitation to the scope of any of  
the present claims. In view of the foregoing description it will  
20 be evident to a person skilled in the art that various  
modifications may be made within the scope of the invention.

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**Claims**

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## CLAIMS:

10 1. A method for forming a conjugated polymer which is doped by a dopant comprising the steps of:

15 (a) adding a doping agent comprising a dopant moiety to a solution comprising the conjugated polymer or a precursor thereof and, optionally, a second polymer, the dopant moiety being capable of bonding to the conjugated polymer, precursor thereof or the second polymer;

20 (b) allowing the dopant moiety to bond to the conjugated polymer, precursor thereof or the second polymer to perform doping of the conjugated polymer;

25 characterised in that the amount of doping agent added in step (a) is less than the amount required to form a fully doped conjugated polymer.

30 2. A method according to claim 1, wherein the amount of doping agent added in step (a) is in the range of less than 10-20% of the amount required to form a fully doped conjugated polymer.

35 3. A method according to claim 1 or claim 2, wherein the amount of doping agent added in step (a) is sufficient to form a 0.1% to 5% doped conjugated polymer.

40 4. A method according to claim 3, wherein the amount of doping agent added in step (a) is sufficient to form a 1% doped conjugated polymer.

45 5. A method according to any one of the preceding claims, wherein the doping agent is a protonic acid doping agent.

50 6. A method according to claim 5, wherein the dopant moiety is selected from the group consisting of a phosphonic acid group, a sulfonic acid group, a fluoroalkyl carboxylic acid group or an indene carboxylic acid group.

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5        7. A method according to any one of claims 1 to 5, wherein the dopant moiety comprises a precursor to the dopant.

10      8. A method according to claim 7, wherein the precursor dopant moiety comprises phosphonate or sulfonate.

15      9. A method according to claim 8, wherein step (c) includes heating the dopant moiety to generate the dopant.

20      10. A method according to any of the preceding claims, wherein step (b) includes cleaving the dopant moiety from the conjugated polymer, precursor thereof or the second polymer.

25      11. A method according to claim 10, wherein the dopant moiety is cleaved from the intermediate polymer by heating.

30      12. A method according to any one of the preceding claims, wherein the dopant moiety bonds to the conjugated polymer, precursor thereof or the second polymer in step (b) via a spacer group.

35      13. A method according to any one of the preceding claims, further including a step of forming a conjugated polymer from the precursor thereof.

40      14. A method according to claim 13, wherein the precursor of the conjugated polymer comprises a substituted precursor polyelectrolyte PPV.

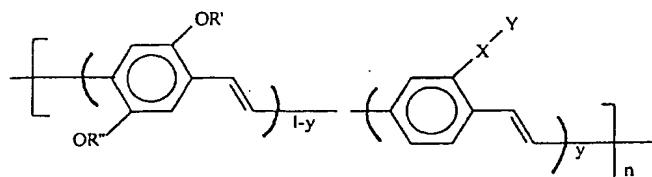
45      15. A method according to any one of the preceding claims, wherein the conjugated polymer comprises substituted or unsubstituted PPV.

50      16. A method according to claim 14 or claim 15, wherein the conjugated polymer comprises the structure shown in formula I or

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II:

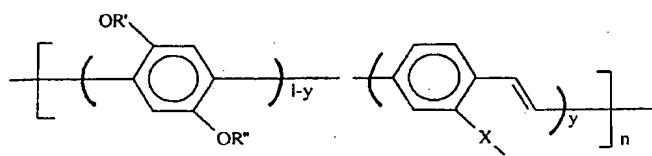
10



(I)

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(II)

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where  $Y$  is the dopant moiety;  $OR'$  and  $OR''$  are each an alkoxy group or H;  $X$  is an alkyl or aryl spacer group or a direct bond;  $y \leq 0.05$  and  $n \geq 10$ .

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17. A method according to any one of the preceding claims, wherein the second polymer is co-polymerised with the conjugated polymer or precursor thereof prior to adding the doping agent in step (a).

40

18. A method according to any one of claims 1 to 16, wherein the second polymer is blended with the conjugated polymer or precursor thereof prior to adding the doping agent in step (a).

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19. A method according to claim 18, wherein the second polymer comprises substituted or unsubstituted PPV.

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20. A method for forming a partially doped polymer comprising the steps of:

(a) adding a doping agent to the polymer or a precursor

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5 thereof, the doping agent being capable of bonding to the precursor or the polymer; and

10 (b) causing the doping agent to leave the precursor or the polymer to form a dopant capable of doping the polymer;

15 wherein fewer moles of the doping agent are added than would be numerically sufficient to fully dope the polymer chain.

20 21. A method according to any one of the preceding claims, additionally comprising the step of:

25 (d) causing the dopant to dissociate to form a substantially uniformly doped conjugated polymer.

30 22. A method according to any one of the preceding claims, additionally comprising the step of processing the solution to form a film layer.

35 23. A doped conjugated polymer preparable by the method as defined in any one of claims 1 to 22.

40 24. A polymer according to claim 23, wherein the doped conjugated polymer has a conductivity of more than  $10^{-9}$ S/cm and less than 1S/cm.

45 25. A polymer according to claim 24, wherein the doped conjugated polymer has a conductivity of from  $10^{-8}$ S/cm to  $10^{-3}$ S/cm.

50 26. Use of a polymer as defined in any one of claims 23 to 25, as a light emissive material.

55 27. A photonic device comprising a polymer as defined in any one of claims 23 to 25.

28. A photonic device according to claim 27, comprising a distributed Bragg reflector.

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5        29. An optical device comprising a polymer as defined in any one  
of claims 23 to 25.

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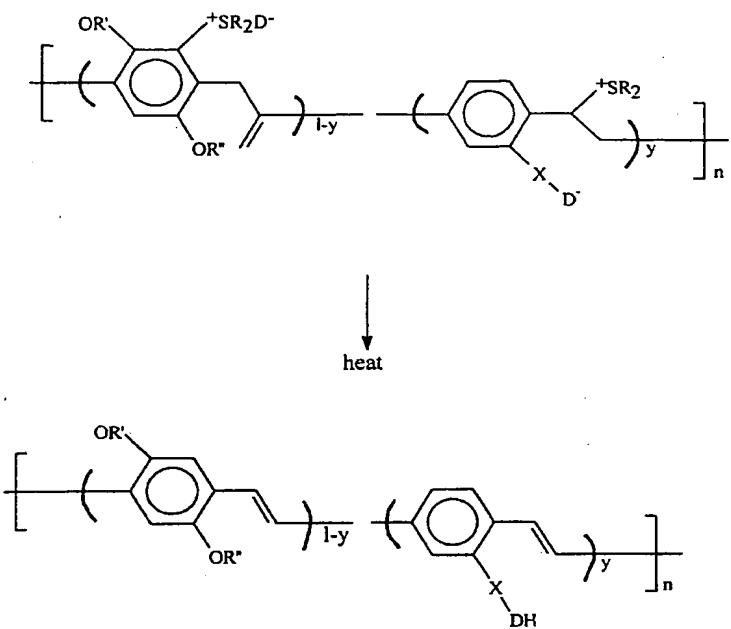


FIGURE 1

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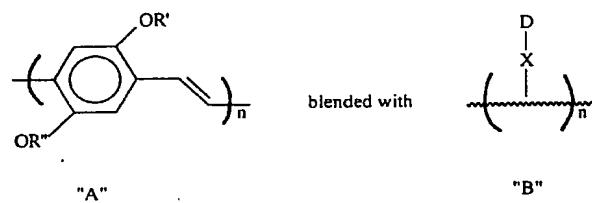


FIGURE 2a

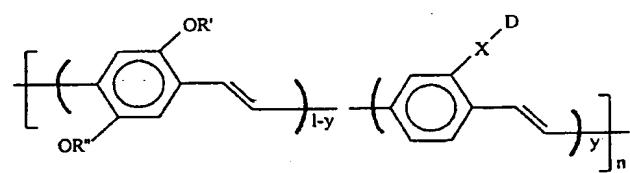
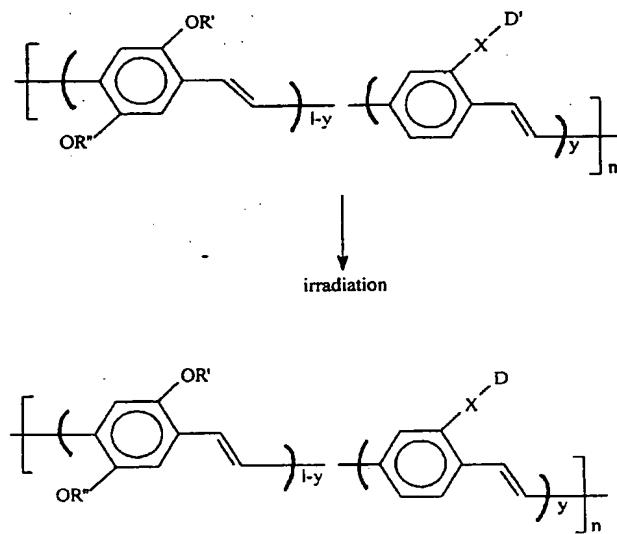
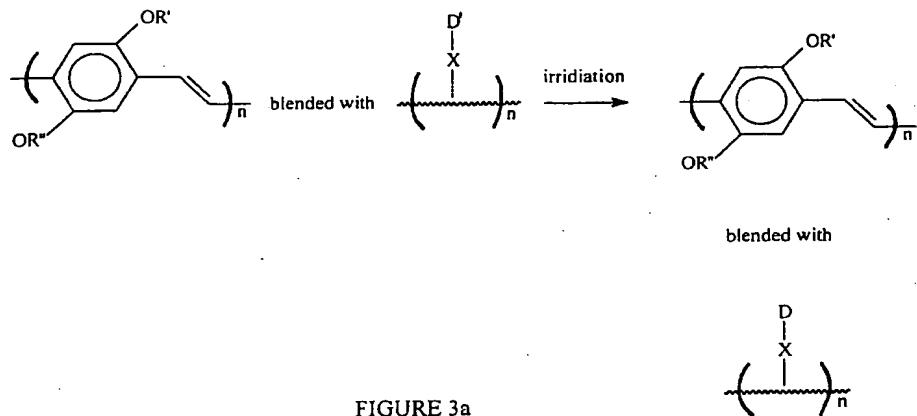


FIGURE 2b

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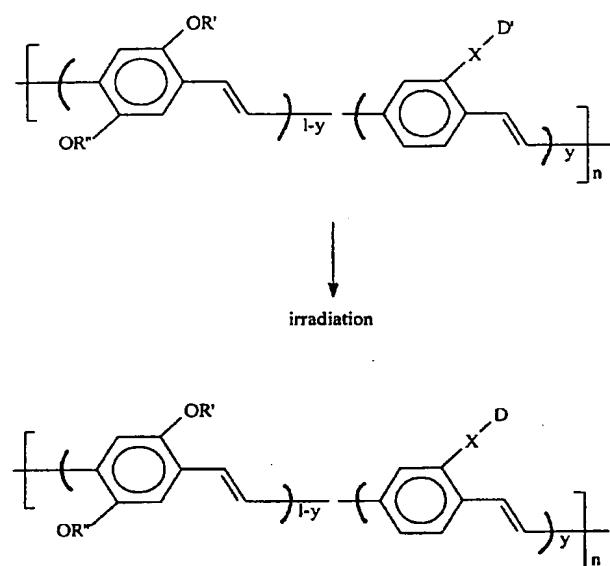


FIGURE 4

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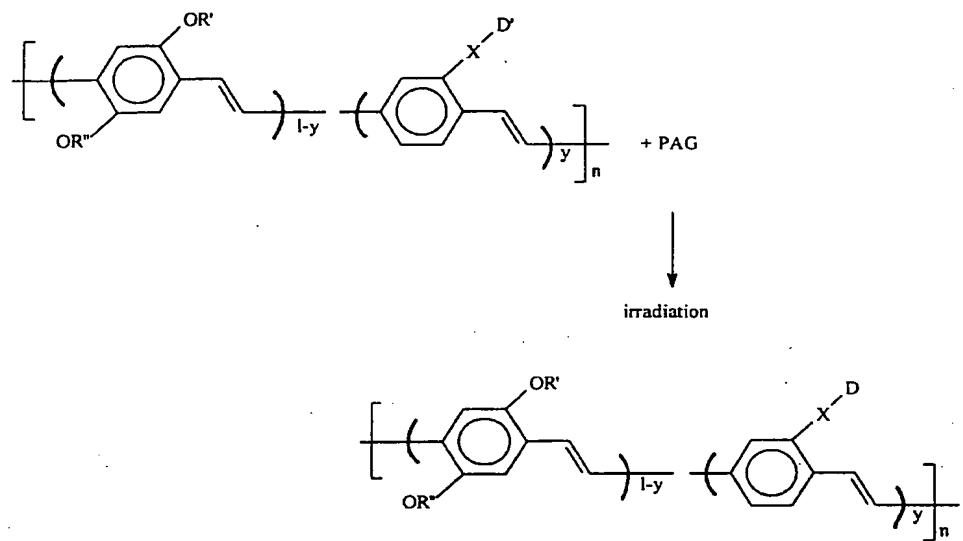


FIGURE 5

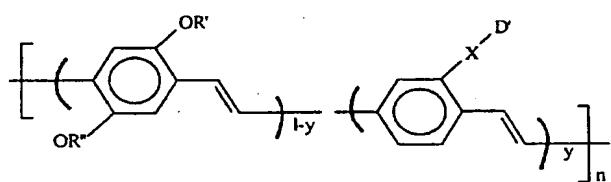


FIGURE 6

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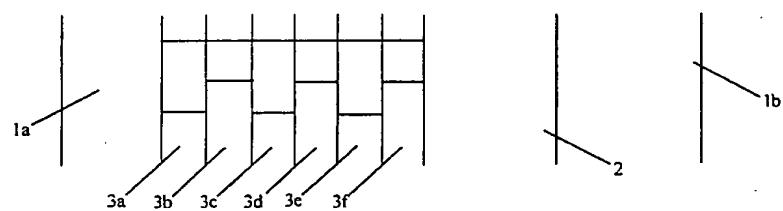


FIGURE 7

**INTERNATIONAL SEARCH REPORT**

Int. onal Application No  
PCT/GB 00/01288

<b>A. CLASSIFICATION OF SUBJECT MATTER</b> IPC 7 H01B1/12 H01L51/20 C08G61/10		
According to International Patent Classification (IPC) or to both national classification and IPC		
<b>B. FIELDS SEARCHED</b>		
Minimum documentation searched (classification system followed by classification symbols) IPC 7 H01B H01L		
Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched		
Electronic data base consulted during the international search (name of data base and, where practical, search terms used) EPO-Internal, WPI Data, PAJ, INSPEC		
<b>C. DOCUMENTS CONSIDERED TO BE RELEVANT</b>		
Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
P, X	WO 00 04593 A (TESSLER NIR ;HO PETER (GB); CAMBRIDGE DISPLAY TECH (GB); FRIEND RI) 27 January 2000 (2000-01-27) page 11, line 1-22 page 29, line 27 -page 35, line 23 ---	1-29
A	US 4 222 903 A (MACDIARMID ALAN G ET AL) 16 September 1980 (1980-09-16) the whole document ---	1,20 -/-
<input checked="" type="checkbox"/> Further documents are listed in the continuation of box C.		<input checked="" type="checkbox"/> Patent family members are listed in annex.
* Special categories of cited documents : "A" document defining the general state of the art which is not considered to be of particular relevance "E" earlier document but published on or after the international filing date "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) "O" document referring to an oral disclosure, use, exhibition or other means "P" document published prior to the international filing date but later than the priority date claimed		
*T* later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention *X* document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone *Y* document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art. *S* document member of the same patent family		
Date of the actual completion of the international search  27 July 2000		Date of mailing of the international search report  03/08/2000
Name and mailing address of the ISA: European Patent Office, P.B. 5818 Patentstaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl. Fax: (+31-70) 340-3016		Authorized officer  De Laere, A

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## INTERNATIONAL SEARCH REPORT

Int'l. Appl. No.
PCT/GB 00/01288

## C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	C.C. HAN ET AL: "Protonic acids: generally applicable dopants for conducting polymers" SYNTHETIC METALS, vol. 30, 1989, pages 123-131, XP000924913 LAUSANNE, CH ISSN: 0379-6779 cited in the application the whole document -----	1,20

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Form PCT/ISA210 (continuation of second sheet) (July 1992)

**INTERNATIONAL SEARCH REPORT**

Information on patent family members

International Application No
PCT/GB 00/01288

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO 0004593 A	27-01-2000	AU 4921499 A	07-02-2000
US 4222903 A	16-09-1980	NONE	